RESEARCH DEPARTMENT

The design of a new free-field sound measurement room: specification and performance

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THE DESIGN OF A NEW FREE-FIELD SOUND MEASUREMENT ROOM: SPECIFICATION AND PERFORMANCE

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SUMMARY

The various requirements laid down in the design of the new free-field room at Kingswood Warren are discussed. Details are given of the building, the acoustic treatment and the associated technical equipment. Acoustic tests on the completed room are described; the frequency range over which free-field conditions can be obtained depends to some degree on the direction of sound propagation, but in favourable circumstances extends to below 50 c/s.

1. INTRODUCTION

For the detailed study of electro-acoustic transducers, and for subjective experiments in which an accurately specifiable sound field has to be produced, it is necessary to avoid reflexion of sound from the walls, floor or ceiling of the test room. It is usually necessary also to reduce extraneous sounds to a very low level. These two requirements can in principle be satisfied by a so-called 'free-field room', in which all surfaces are covered to a considerable depth with acoustic absorbent material, while the structure itself is designed to exclude sound. In practice, however, the approach to the ideal condition of free-field sound propagation with no extraneous noise is limited by economic factors, and a compromise has to be arrived at by taking into account the purpose for which the room is required. This report describes the design of a new free-field room at Kingswood Warren to meet the needs of Electro-Acoustics Group.

Of the various technical operations for which the new room was intended, the following make the greatest demands on the available space: sound insulation studies involving the measurement of radiation from large sheets of material; measurement of the free-field characteristics of microphone or loudspeaker arrays designed for long-range working; investigations into stereophonic reproduction or other aspects of directional hearing, for which widely spaced sound sources are required. With these requirements in mind, the dimensions of the working space remaining after the introduction of the necessary acoustic absorbent material were fixed at 20 feet × 16 feet × 10 feet high, (6·1 m × 4·9 m × 3 m). A working floor offering as little obstruction to sound as possible had to be provided to give easy access to the

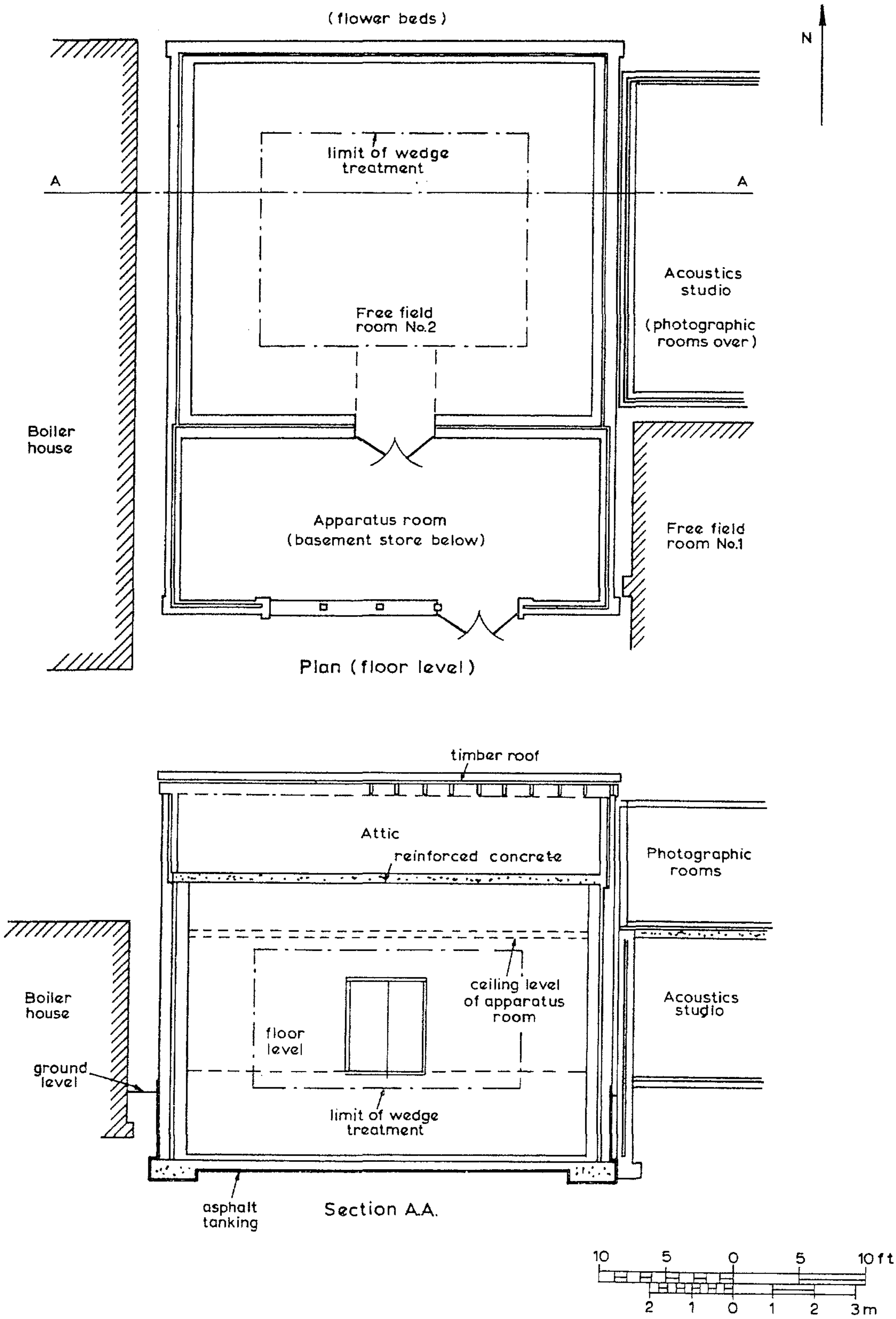


Fig. 1 - General layout of free-field room and adjacent areas

operating area. Consideration was given to the use of a permanent floor of highly tensioned nylon mesh, such as is fitted in some free-field rooms, but this arrangement was eventually rejected in favour of a rigid floor of steel grids, divided into a large number of removable sections carried on stanchions. The working floor had to be mounted at such a height that any apparatus placed at a point mid-way between the true floor and the ceiling of the room would be in a convenient position for a standing operator. To facilitate the movement of heavy equipment in and out of the room, it was essential that the working floor should be at ground level; to meet this requirement, the room had to be sunk into the ground to a depth of 6 feet (1·8 m).

Since many of the investigations to be carried out in the room were concerned with the high-quality reproduction of music, it was necessary that a good approximation to free-field conditions be maintained over the complete audio-frequency range down to 50 c/s; this requirement will be referred to again in Section 4.

The maximum sound levels to be generated in the room were expected to be of the order of +120 dB with reference to 2×10^{-4} dynes/cm^2 and it was not necessary therefore to take precautions, as in the case of some free-field rooms for work involving high-intensity sound, against damage to the acoustic absorbent material through excessive vibration.

Fig. 1 shows the general layout of the free-field room and of the adjacent areas and Fig. 2 a photograph of the interior.

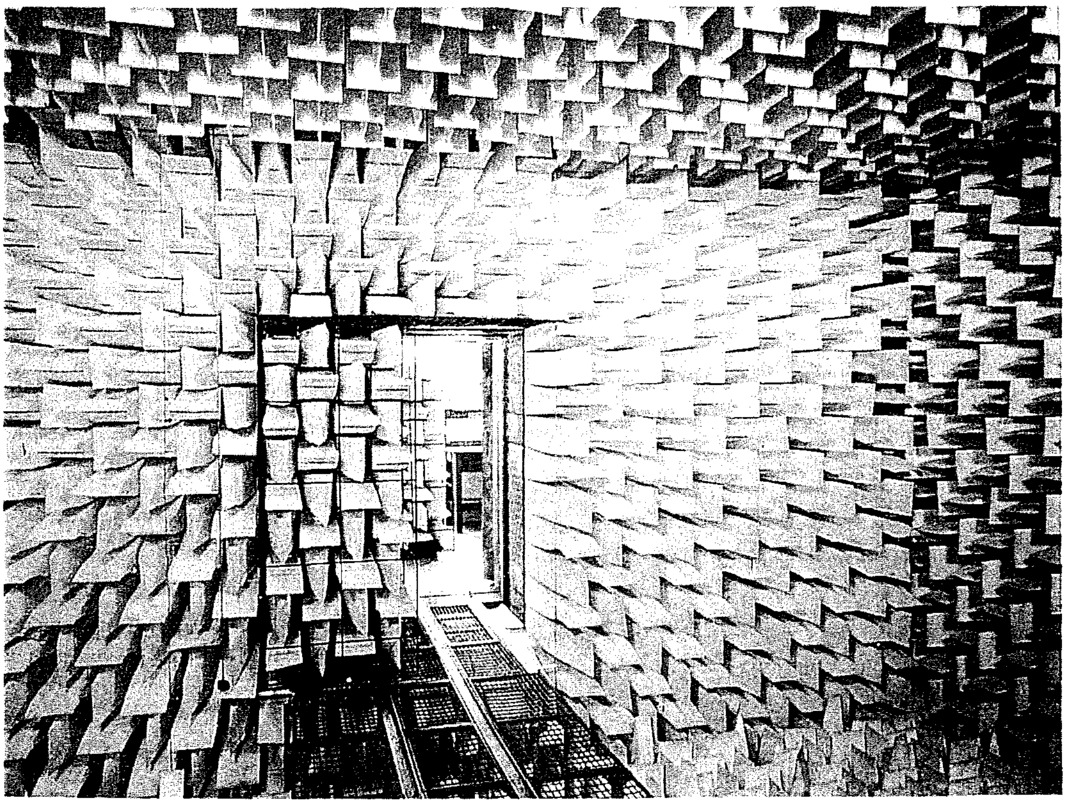


Fig. 2 - Interior of free-field room (working floor partially removed)

2 SOUND INSULATION

The most intense noises against which protection is required are those of aircraft flying at a low altitude immediately over the room and of test sounds or programme in an adjacent studio used for experiments in room acoustics. Either noise may be expected to reach a level of +100 dB with reference to 2×10^{-4} dynes/cm^2 in octave bands over most of the audible spectrum, with slight reductions below 125 c/s and above 4 kc/s.

As will be seen from Fig. 1, the roof and two sides of the room above ground level are exposed to aircraft noise, the front face being protected by an adjoining apparatus room and one side by the acoustics studio, over which is built a photographic studio and office.

If the pressure level outside is applied to an area A of wall or ceiling, the reduction L in level inside the room is given by

$$L = I + 10 \log_{10}\left(\frac{1}{4} + \frac{A}{R}\right) \text{dB}$$ [1]

where I is the sound reduction index (S.R.I.) of the wall or ceiling in dB and R is the 'room constant' given by $S\bar{a}/(1 - \bar{a})$ in which S is the total area of the internal surfaces of the room and $\bar{a}$ their mean absorption coefficient.

In a free-field room, $\bar{a}$ must necessarily be nearly unity, so that the term A/R can be neglected; the second term of the above expression then becomes 6 dB and the effective sound insulation of the construction is thus increased by this amount.

It has been established[2] that the transmission loss through a porous layer adjacent to a solid wall is small or even negative at low frequencies, but roughly additive to that of the wall On this basis, the loss through the wedges was conservatively estimated as nil at 62 c/s, rising to 34 dB at 8 kc/s.

The requirements for maximum acceptable background noise are based on two types of test. Subjective tests may require the background to be below the threshold of hearing whilst objective measurements of the self-generated noise of microphones, for instance, require a still lower background noise level at low frequencies. A maximum of +15 dB with reference to 2×10^{-4} dynes/cm^2 in any octave band was assumed at frequencies up to 250 c/s above which the threshold of hearing of bands of noise in a diffuse sound field was adopted.

The considerations of external noise, acceptable background noise inside and necessary corrections as outlined above, finally led to the following requirements for the sound reduction indices of the ceiling and walls.

Frequency	62	125	250	500	1000	2000	4000	8000 c/s
S.R.I.	68	70	70	70	70	70	69	61 dB

If we consider only the requirements of subjective testing, we obtain instead at low frequencies

Frequency	62	125	250 c/s
S.R.I.	43	61	66 dB

To attain the first set of figures would need a construction which was very uneconomical for middle and high frequencies. To attain the second set of figures would be relatively easy. The construction described in Section 4 represents a compromise between the requirements for subjective tests and objective measurements which may result in occasional interference in some objective measurements at low frequencies.

The isolation of the room from solid-borne impact sounds was also considered. There are no underground sources of vibration or noise, and isolation is therefore required only in respect of footsteps or other impacts at ground level. The room is protected from close approach of footsteps by the apparatus room at the front and flower beds at the back. One side adjoins the studio and the other is flanked by a passage which could be barred if necessary. There is a minimum of 20 ft (6·1 m) of earth between the nearest point of approach and the foundations of the free-field room. This, together with the asphalt tanking over all parts below ground level, was expected to give sufficient protection against footsteps and other sources of ground-borne sound.

3. ACOUSTIC TREATMENT

When the building was first planned it was necessary to decide how much space would be taken up by the sound absorbent lining. Since the aim of the design was to simulate free-field conditions at all frequencies down to 50 c/s, it was decided that the so-called 'cut-off frequency' at which the reflexion coefficient for normal incidence rises to 10% should be in the region of 45 c/s. From a study of the literature and experience with an existing room built in 1950, it was estimated that the desired result could be achieved by allowing a depth of 5 feet (1·5 m) for acoustic treatment, this figure to include any air space between the absorbent material and the wall. To give the required working space, the dimensions of the bare room were therefore fixed at 30 ft × 26 ft × 20 ft high (9·1 m × 7·9 m × 6·1 m).

From published data on the design of free-field rooms, it is clear that the most effective form of acoustic treatment consists of a series of wedges or pyramids of absorbent material completely covering the walls, floor and ceiling. There is as yet no satisfactory theory by which the reflexion coefficient of such tapered structures can be calculated from their dimensions and the physical constants of the material employed. Most of the theoretical analyses given in the literature[3-9] are based only on the flow resistance of the material and do not take into account the elastic properties and the dissipation of energy by mechanical hysteresis; in practice, especially with the more elastic materials, it is the mechanical properties rather than the flow resistance which largely determine the sound absorption at low frequencies. However, even when attempts have been made to allow for mechanical movement of the material, the agreement between the predicted and the measured

performance of the absorbers is not very good. In the circumstances, therefore, the choice of material and dimensions for the wedge absorbers was made on the basis of experiment.

In the free-field rooms built before about 1955, the absorbent materials employed were usually of the glass fibre or mineral wool type; these have an unfortunate tendency to shed sharp particles which are a potential danger to the eyes and other delicate surfaces. In recent years, a variety of alternative materials has become available; among those tested for the present purpose were rubberised hair, compressed woodwool, a new resilient type of glass wool fibre, foamed formaldehyde and various types of foamed polyurethane. Of these, the polyurethane foam offered the most promise but some material of this type was found to have pronounced mechanical resonances which adversely affected the absorbent properties, and it was not until a new form of expanded polyurethane having a higher degree of mechanical hysteresis became available that an acceptable performance could be relied on in production. Further details of these tests and of the final form of wedge adopted have been given in an earlier report.[10]

In the course of the investigation to determine the optimum material and dimensions of the wedges, consideration was given to the artifice, adopted by some workers,[11] of providing Helmholtz resonators behind the absorbent material, the opening into each resonator being formed by a narrow gap between adjacent wedges. Experiments indicated, however, that even under the most favourable conditions, any increase in absorption obtained by this means was confined to a narrow frequency band and was accompanied by a decrease in absorption at other frequencies. It is thought that some of the effects attributed in the literature to the action of a Helmholtz resonator may in fact have been due to interference between one wave which is reflected from the front of the acoustic treatment and another which has penetrated the material and been reflected from the wall behind.

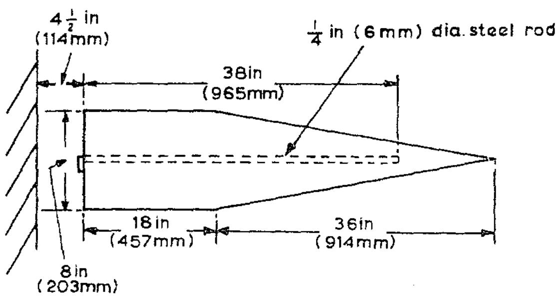


Fig. 3 - Dimensions and position of polyurethane wedge

The dimensions and position of the wedge finally adopted are shown in Fig. 3. An allowance of 6 in. (150 mm) was originally made for the air gap at the rear of the wedge, but with the type of polyurethane foam finally adopted, the optimum gap length was found to be 4½ in. (110 mm). The overall depth of the acoustic treatment is therefore 1½ in. (40 mm) less than that originally estimated and the working space in the room correspondingly increased. Each wedge is reinforced by a ¼ in. (6 mm) diameter steel rod, which is inserted into a hole previously made by a heating element on the end of a probe. As explained in the previous report,[10] the principal function of this rod is to lower the cut-off frequency by adding mass to the wedge; for the wedges used on the floor of the room, these rods are divided into sections joined by a spiral spring, forming a flexible element which, in the event of anyone falling on to the acoustic treatment, will fold over without causing injury. As a further safety precaution, the fixed portion of every unused stanchion is covered with a loosely fitting cylindrical cap of hard rubber; each cap is surmounted by a polyurethane foam wedge 11 in. (280 mm) high to reduce sound reflexion at frequencies for which the flat top presents an appreciable obstacle.

In mounting the wedges in the free-field room, a layer of glass fibre was used to cover any bare surfaces appearing at the junctions of walls, floor and ceiling.

Because of the predominant part played by the mechanical resonance phenomena in determining the reflexion coefficient of the wedges, it was not possible to check the consistency of the material in production by tests on a small specimen; it was therefore necessary to have a number of full-sized wedges cut from each batch as samples. These samples, amounting to about 2% of the material produced, were tested for reflexion coefficient in the critical frequency range below 150 c/s; in the event of the results falling outside tolerance in this respect (fortunately an infrequent occurrence) the manufacturer was able to utilise the batch for other purposes. Fig. 4 shows the spread of the results obtained with 120 sample wedges, tested in groups of four.

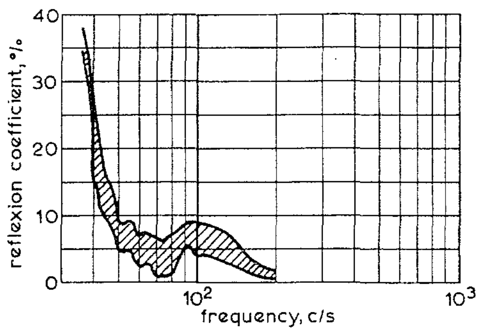


Fig. 4 - Reflexion coefficient of polyurethane wedges, showing spread for 120 samples tested in groups of four

In the following table, the efficacy of the form of absorbent adopted (first item) is compared with that of others referred to in the literature. To give a common basis of comparison, a figure of merit is derived by dividing the wavelength λ_o at the cut-off frequency (for 10% reflexion coefficient) by D, the overall depth of the acoustic treatment.

ORIGIN OF DATA	DEPTH D AND TYPE OF TREATMENT	CUT-OFF FREQ. C/S	WAVELENGTH (λ_o) AT CUT-OFF FREQ.	RATIO λ_o/D
Report L-055	60" foamed Polyurethane ether wedges	48	271"	4·75
Report L-055	60" light glass fibre wedges	50	260"	4·35
Meyer et al, Akustische Zeitschrift 5, 1940, page 352	39·4" cones of packed glass wool	80	162"	4·15
Beranek, J.A.S.A., 18, 1, 1946, page 140	57" glass fibre	70	186"	3·3
Meyer et al, Akustische Beihefte 3, 1953, page 409	41" high density glass fibre wedges	70	186"	4·55
P.O. Research Report No. 12680, June 1949	37" glass fibre wedges	105	137"	3·7

ORIGIN OF DATA	DEPTH D AND TYPE OF TREATMENT	CUT-OFF FREQ. C/S	WAVELENGTH (λ_o) AT CUT-OFF FREQ.	RATIO λ_o/D
Kurtze, Akustische Beihefte 2 SAB 104, 1952	25·6" glass fibre wedges	98*	133"	5·1
Tanner and Jamroz, Audio Eng. Soc. Convention 1962	60" glass fibre wedges	63	207"	3·45
Duda and Oppenheim, Audio Eng. Soc. Convention 1962	60" glass fibre wedges	68	192"	3·15
N. Olson, J.A.S.A., Vol. 33, No. 6, page 767	36" glass fibre wedges	80	162"	4·55
Ebel and Maurer, Akustische Beihefte 4, 1952, page 253	24" glass wool wedges	160	81·5"	3·4
Epprecht et al, Akustische Beihefte 2, 1954, page 568	23·5" glass fibre and steel wool wedges	120	108"	4·55
Hardy et al, J.A.S.A. Vol. 19, No. 6, Nov. 1947, page 988	29" glass fibre wedges	115	113"	3·9
Rivin, Soviet Physics Acoustics Vol. 7, No. 3, Jan - March 1962	43" dense glass fibre wedges	70	186"	4·35
Kraak et al, Hochfrequenztechnik und Elektroakustik, Feb. 1960, page 1	45" glass wool-stuffing wedges	60	217"	4·75
Provenko and Rivin, Soviet Physics Acoustics, Vol. 5, No. 3, 1960, page 387	43" glass fibre wedges	60	217"	5·0
Olson, J.A.S.A., Vol. 15, No. 2, 1943, page 96	96" sheets of Ozite	40	325"	3·55
Bausch and Schubert, Frequenz Oct. 1959, Vol. 13, page 234	30·5" Sillan wedges	100	130"	4·25
Ellison and Miller, Journal of Inst. M.E., Oct. 1963, Vol. 178, Part 1, No. 2, page 53	48" Foamed Polyurethane ester wedges	81	163"	3·4
Schubert and Scholze, Tech. Mitt. B.R.F. Sept. 1960, page 101	47" sheets and wedges of glass wool	65	200"	4·25

* 14% reflexion at 200 c/s

It will be seen that the value of 4·75 for λ_o/D obtained with the polyurethane wedges employed in the present project has been equalled or exceeded only with forms of treatment having a cut-off frequency of 60 c/s or above.

The cost of the acoustic treatment of any free-field room is high and a comparison of costs of differing forms of treatment is therefore of interest. The price of the polyurethane wedges of the type employed in the present room was 20s 6d each, the only other material available giving comparable results appears to be Sillan, a German product, which is about four times the price given above. It may be noted that one of the types of polyurethane wedge, mentioned in Report L-055, which initially gave promising results but had to be abandoned as the material was not reproducible, would have cost only about 17s 6d. As mentioned earlier, the framework holding the wedges in position was made from a standard form of steel mesh employed for reinforcing concrete, the cost being only 1/- per wedge. The 38-inch (0·96 m) rods inserted in the wedges together with the tip supports, also described in Report L-055, cost an additional 1/- per wedge.

The total number of wedges employed was 5192. The construction time for the framework and for the wedge supports and the installation of the wedges amounted to approximately 3160 hours, i.e. 0·6 hours per wedge. This compares with a figure of 1¼ hours per wedge for the free-field room installed at the Post Office Research Station[12] in 1947.

4. STRUCTURE

For reasons given elsewhere in this report, the floor of the room was sunk to a depth of 6 ft (1·8 m). The S wall is protected from aircraft noise by the apparatus room and the space above it and the E wall by the studio, though this is itself a source of noise. The W wall is shielded by the boiler-house. The only completely exposed wall, the N wall, has a height of 14 feet (4·3 m) above ground level and a length of 28 feet (8·5 m). The recommended wall construction was two leaves of 9 in. (220 mm) brickwork with a gap of 8 in. (200 mm) between them. For the roof, 8 in. (200 mm) of concrete was recommended with a working space above roofed with 1 in. (25 mm) of timber or its equivalent in sound insulation. In the final design the roof space was made approximately 6 feet (1·8 m) high and was closed by 2 in. (50 mm) Stramit. For structural reasons and to economise in space, the cavity in the walls was reduced to 3 in. (75 mm). The roof insulation was expected to be adequate but the walls would fall short of the desired insulation even having regard to the relatively small exposed area. It was argued, however, that the thickness of the exposed wall could be increased without difficulty at a later date if it were found to be inadequate.

The inner shell of the free-field room is entirely isolated by the cavity from the outer walls, apart from having a common heavy foundation and compliant fillings round the door frames and in the attic above. The reinforced concrete roof is 9 in. (220 mm) thick and supported by integral rolled steel joists resting entirely on the inner walls. Above this the walls are of two 4½ in. (110 mm) leaves with a 2 in. (50 mm) cavity connected by flexible wall-ties consisting of two galvanised iron strips moulded into a block of cold-cured latex rubber. This construction is also used for the walls of the apparatus room and the storage space above.

It was not considered necessary to extend the outer 9-inch (220 mm) leaf of the S wall of the free-field room above the ceiling of the apparatus room. This ceiling lies approximately 4 feet (1·2 m) below the main ceiling slab of the free-field room, but the storage space is entirely protected by other walls from external sounds. The cavity which therefore appears along one edge of the floor of the storage space was closed with strips of expanded polystyrene lightly wedged into place, largely to prevent small objects from falling into and bridging the cavity.

Protection from test sounds generated in the studio is provided by the two leaves of 9-inch (220 mm) brickwork of the free-field room together with two 4½-inch (110 mm) leaves making up the studio wall. The measured sound reduction index of the combination is 70 dB at 62 c/s, rising with frequency, and is therefore adequate.

Measurements made before installation of the wedges showed that the sound reduction between the studio and the free-field room was 70 dB up to 200 c/s, thereafter rising at 4 dB per octave.

The sound reduction from behind through the double 9-inch (220 mm) wall was 64 dB up to 200 c/s with the room complete, rising to 90 dB at 500 c/s. Both these measured results are satisfactory except those through the back wall at the lowest frequencies.

It has not been possible at the time of writing to measure the sound reduction through the roof which is expected to be greater than either of the above.

5. TECHNICAL EQUIPMENT

The only piece of technical equipment permanently installed in the free-field room is a 2-inch (50 mm) diameter vertical shaft which projects through a hole in the ceiling and is used to support microphones, or loudspeakers up to 1 cwt in weight. This shaft can be rotated by remote control to facilitate the measurement of polar response characteristics. The polar characteristics of a loudspeaker are normally measured by a microphone mounted on a horizontal boom attached to the lower end of the shaft. The error in rotational position does not exceed $\pm \frac{1}{4}^\circ$ when a 2 lb microphone is carried at a radius of 5 feet (1·5 m) - the worst condition to be expected in practice.

To obviate the necessity for trailing leads, a multicore cable for a standard capacitor microphone together with two screened pairs for the connection of other equipment are brought down inside the shaft and terminated in appropriate connectors.

The lower end of the shaft must be capable of being brought to within 5 feet 4 inches (1·6 m) of the floor so as to be within comfortable reach of all operating personnel. On the other hand, in order to clear the working area of the room the shaft has to be retracted to within 6 in. (150 mm) of the ceiling wedge tips; to meet these requirements, a vertical travel of 3 feet 2 inches (0·97 m) is necessary. The vertical position of the shaft is regulated by a motor drive remotely controlled by a small key switch on an extension lead. To facilitate

accurate vertical positioning, the shaft moves at a low speed when first switched on but changes to a higher speed automatically after a few seconds, thus saving time where a large movement is needed.

The equipment for raising, lowering and rotating the shaft is mounted in a frame resting on two girders which support the ceiling. The complete assembly, shown in Fig. 5, can be transferred to any one of three positions, for which holes in the ceiling are provided.

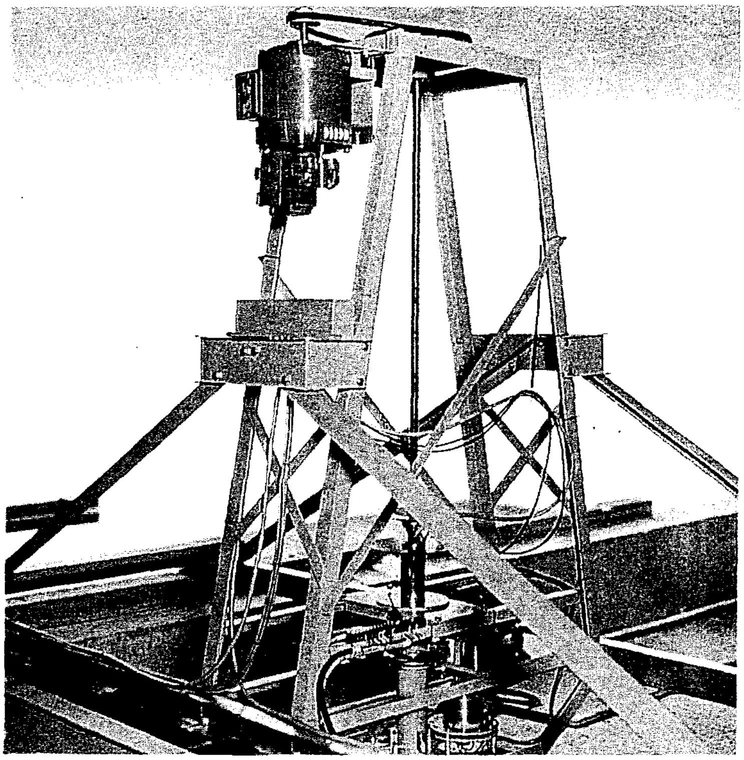


Fig. 5 - Retractable shaft for rotating a microphone or loudspeaker; view from above free-field room

As a sound source for use in microphone testing, the special loudspeaker shown in Fig. 6 is provided; the enclosure is designed to present the smallest possible frontal area to reduce re-reflexion of any sound reflected back to it by the microphone. The axial frequency characteristic of the loudspeaker is uniform within ± 2·5 dB from 40 c/s to 18 kc/s; this frequency characteristic is achieved by dividing the frequency band into three parts, each dealt with by an appropriate unit. The loudspeaker is carried by a light stand, designed to be acoustically inconspicuous, by means of which it may be supported by the grid floor or by the floor stanchions in one of a number of fixed positions.

The electronic measuring equipment associated with the free-field room is bay-mounted in the adjoining apparatus room. In addition to the usual facilities for continuous tracing of transducer frequency characteristics, provision is made for synchronizing the curve tracing equipment with the rotatable shaft in the free-

Fig. 6 - 3-unit loudspeaker used as sound source in microphone testing

field room for continuous plotting of polar response characteristics. The equipment also includes an interrupter and synchronized oscilloscope display for transient response measurements.

6. ACOUSTIC TESTS

6.1. Experimental Details

Several methods of determining how nearly a free-field room approximates to free space have been suggested in the literature.

In one of the procedures recommended in B.S.I. Specification No. 2498:1954, which is concerned with the testing of loudspeakers, 'a microphone and loudspeaker are set up in the room, separated as for taking the frequency characteristic of the loudspeaker, but fixed together so that the combination of microphone and loudspeaker can be moved to different parts of the room without altering their relative positions. The overall frequency characteristics of the combination should be taken for at least four asymmetrical positions in the room so chosen that the microphone positions are at least a quarter wavelength apart at the lowest frequency at which the room is to be used. The degree of approximation to free-space conditions for the particular position of the microphone in relation to the loudspeaker can be estimated from the maximum differences between the frequency characteristics at the different positions'.

The above procedure is open to the objection that at low frequencies the wavelength of sound may be comparable with or greater then the distance between the parallel absorbing surfaces in the room; under these conditions the room acts as a lined duct[13] in which the rate of attenuation of sound pressure with distance exceeds the inverse distance law which applies to free-field conditions. In the test described, this excess attenuation takes the form of a bass cut which is constant and does not therefore appear in the result.

In another method[14], a loudspeaker and microphone combination is arranged so that it can be rotated about the axis of the loudspeaker and the variation, with angle, in the microphone output noted. The measurement is performed for various distances of the microphone from the loudspeaker and the departure from constant radiated power calculated. However, in practice this method limits the position of the source to the room centre and the measurements to the horizontal plane.

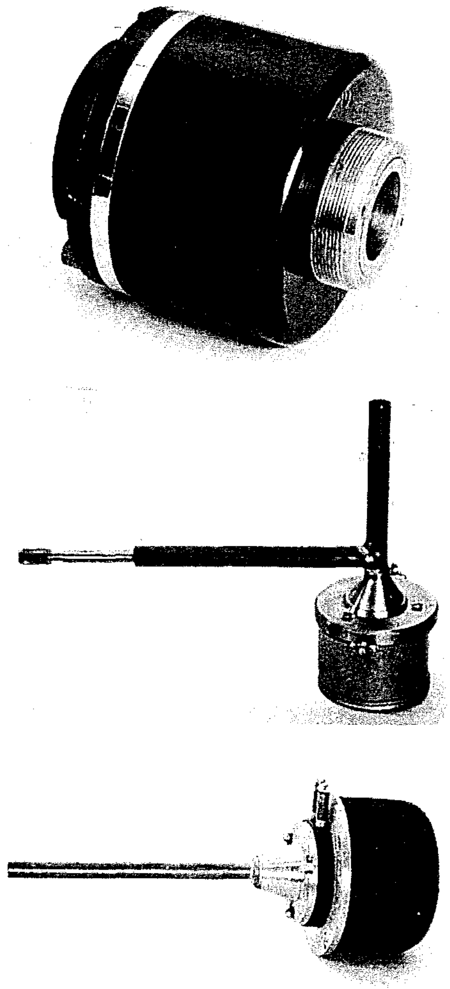
The use of a highly directional microphone has been suggested[15] to determine the level of reflexions from the walls of the room; alternatively, very short pulses of sound may be generated and the level of the reflexions measured. Neither of these tests can, however, be applied at the lower end of the audio-frequency range; in the first case, the necessary directivity is not obtainable while in the second the duration of a cycle is of the same order as the time interval before the arrival of the first reflexion.

The form of test adopted in the present instance is that given as an alternative in the B.S.I. specification already cited. A point source of sound is set up and the pressure-distance relationship explored by means of a moveable microphone. Under free-field conditions the sound pressure level from a point source varies inversely with distance and the performance of the room is expressed in terms of the maximum deviation of the sound pressure from this law; tests are carried out along differing paths, for example, along a diagonal or an axis of the room.

It is essential that the loudspeaker employed for the test should approximate closely to a point source, thus giving omnidirectional radiation. If this requirement is not met, optimistic results will be obtained if measurements are made along the acoustic axis of the loudspeaker. In order to simulate a point source at any frequency between 40 c/s and 15 kc/s, it was necessary to use different loudspeakers for different parts of the range. Between 40 c/s and 150 c/s a totally enclosed loudspeaker, type LS3/1, was employed; this has a cabinet of dimensions 30 in. × 18 in. × 12 in. (760 mm × 460 mm × 300 mm) with an aperture 10 in. × 7 in. (250 mm × 180 mm) and the sound pressure produced was uniform within 1 dB in all directions. Between 200 c/s and 2 kc/s, the horn driver unit shown in Fig. 7(*a*) was used as the sound source. For the frequency range 2 kc/s to 8 kc/s a still smaller radiator was required, and to this end a driver unit was fitted with a ½-inch (13 mm) diameter extension tube, as shown in Fig. 7(*b*); to increase the efficiency and reduce effects of non-linearity the device could be tuned to any required frequency by means of a stub let into the side of the main tube and provided with an adjustable piston. At frequencies from 10 kc/s to 15 kc/s a similar device, shown in Fig. 7(*c*), employing a ¼-inch (6 mm) diameter extension tube without a tuning stub was used.

To avoid unwanted discrimination between direct and reflected sound, it is clearly essential in testing for residual reflexions in a free-field room that

the microphone as well as the loudspeaker should be omnidirectional. A Beyer moving-coil microphone type M100 was employed. The diameter of the diaphragm is approximately ½ in. (13 mm) and the variation in sensitivity with direction of incidence is not greater than 1 dB up to a frequency of about 5 kc/s. To make the microphone less directional at higher frequencies, recourse was had to a device due to Romanov[16]; this consists of a disk of acoustic resistance material, a little larger in diameter than the microphone, mounted a short distance from the diaphragm. With the Romanov disk the polar response of the Beyer M100 microphone was uniform within 3 dB up to 12 kc/s.



(a)

(b)

(c)

Fig. 7(a) to 7(c) - Sound sources used in acoustic tests to give spherical radiation

To measure the variation in sound level with distance in the horizontal plane, the microphone was suspended from a light carriage, running on an overhead track, as shown in Fig. 8; the variation in output from the microphone was registered on the chart of a level recorder. The problem of interpreting the resulting curves was eased by employing the following device, which appears to have been first used in this form by Rivin[17] in testing a free-field room in Moscow. The output from the microphone was applied to a compensating potentiometer mounted alongside the track, the moving contact being attached to the microphone. The potentiometer was so connected that for a constant input the output from the wiper was proportional to distance d from the source. If the sound level varied exactly as the inverse distance, the output from the potentiometer would be the product $d \times 1/d$ and would therefore remain constant; any deviations from this law are thus indicated on the chart as departures from a constant level and by the use of a suitably expanded scale can be observed with considerable accuracy.

For measurements involving vertical movement, the microphone was attached to an endless cord passing over pulleys at top and bottom, the slide wire being replaced by a multiturn potentiometer coupled to the driving shaft.

Measurements were made over the paths shown in Fig. 9. Paths (*a*), (*b*) and (*c*) were chosen to give the greatest distances possible in the available space along the directions shown, (*a*) along a diagonal and (*b*) along the longer axis of the room; in both these cases the microphone was suspended halfway between the roof and floor treatment. Path (*c*) was similar to that of (*a*) but with the microphone only 1 foot from the tips of the floor wedges. For path (*d*) the sound source was in the room centre - the position in which a loudspeaker under test would be placed;

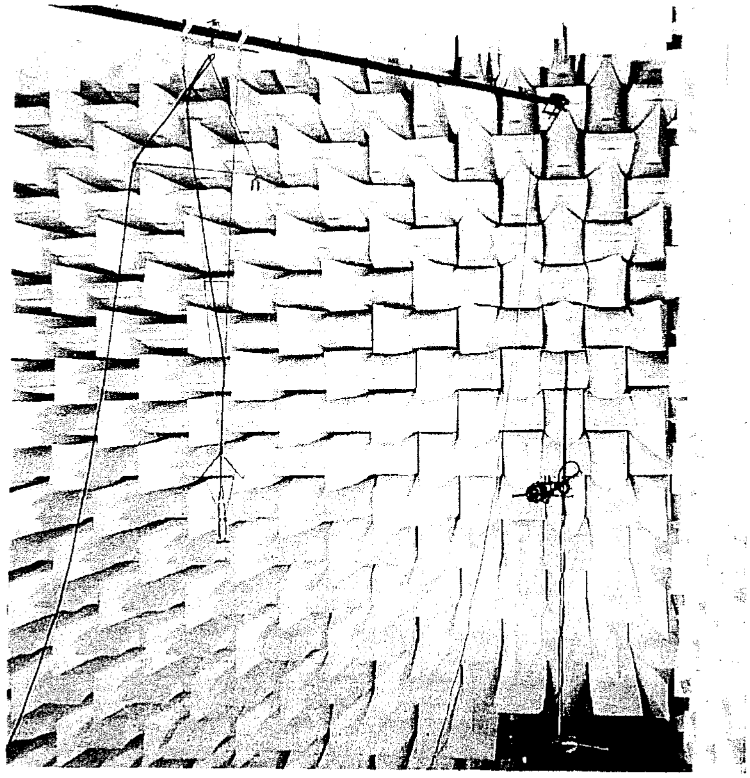


Fig. 8 - Travelling microphone used for acoustic tests

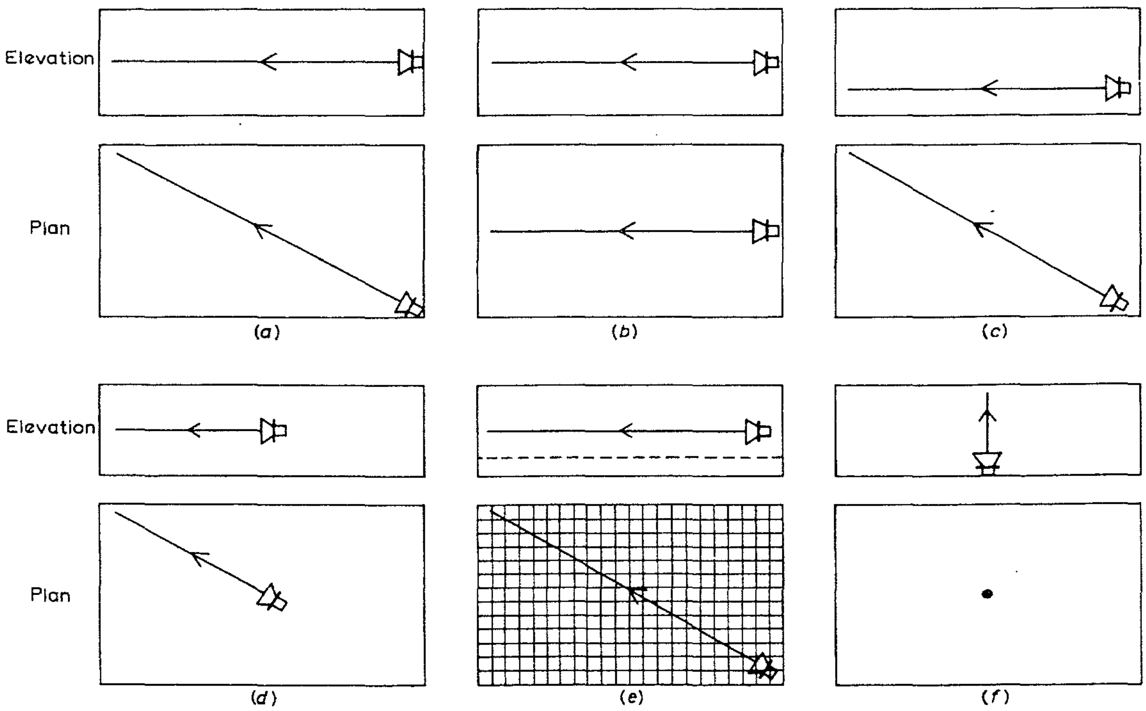


Fig. 9 - Paths along which variations in sound pressure were measured

with the source in the centre the sound was incident more nearly at right angles to all the acoustically treated surfaces than for any other location, and the difference between the results for this and other source positions therefore gives an indication of the variation in absorbent properties of the treatment with angle of sound incidence. Path (*e*) was similar to (*a*) but with the grid floor in position. Path (*f*) was in the centre of the room in the vertical plane, with the sound source about 1 foot above the tips of the floor wedges.

6.2. Results

Fig. 10, curves (i), (ii) and (iii), gives typical results as they appear on the recorder chart showing the deviations from the inverse distance law as a function of distance. In curve (i), measured at 46 c/s, it will be seen that the deviation is mainly due to the excess attenuation mentioned at the beginning of the section rather than to standing waves in the room; this implies that the wave front will have an additional curvature superimposed on it and some types of measurement in the room will therefore be affected.

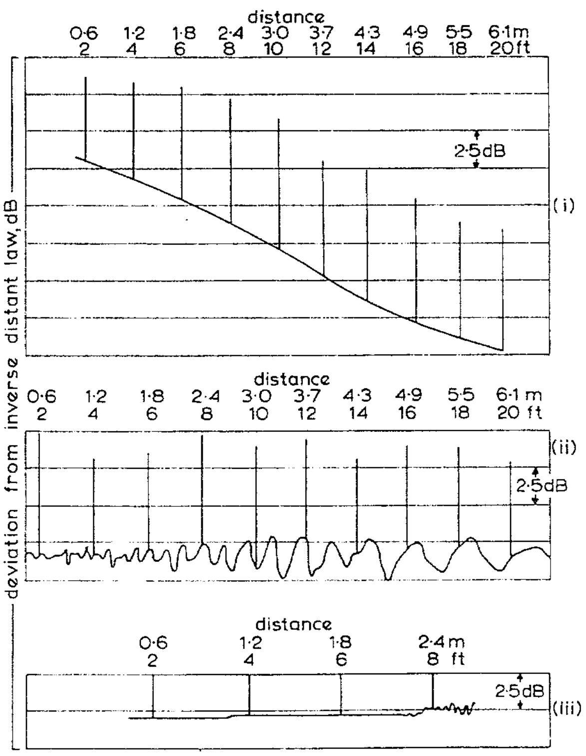


Fig. 10 - Typical examples of recorder chart traces obtained in acoustic tests

In Figs. 11 to 16, the maximum deviation from the inverse distance law is plotted, irrespective of sign, as a function of frequency for the different paths shown in Fig. 9. It will be seen from Fig. 11 that up to a distance of 4 feet (1·2 m) from the source on path (*a*) the inverse distance law is followed within about 1 dB over the frequency range 55 c/s to 15 kc/s. In Fig. 12 the departure from the inverse distance law attributable to excess attenuation at low frequencies

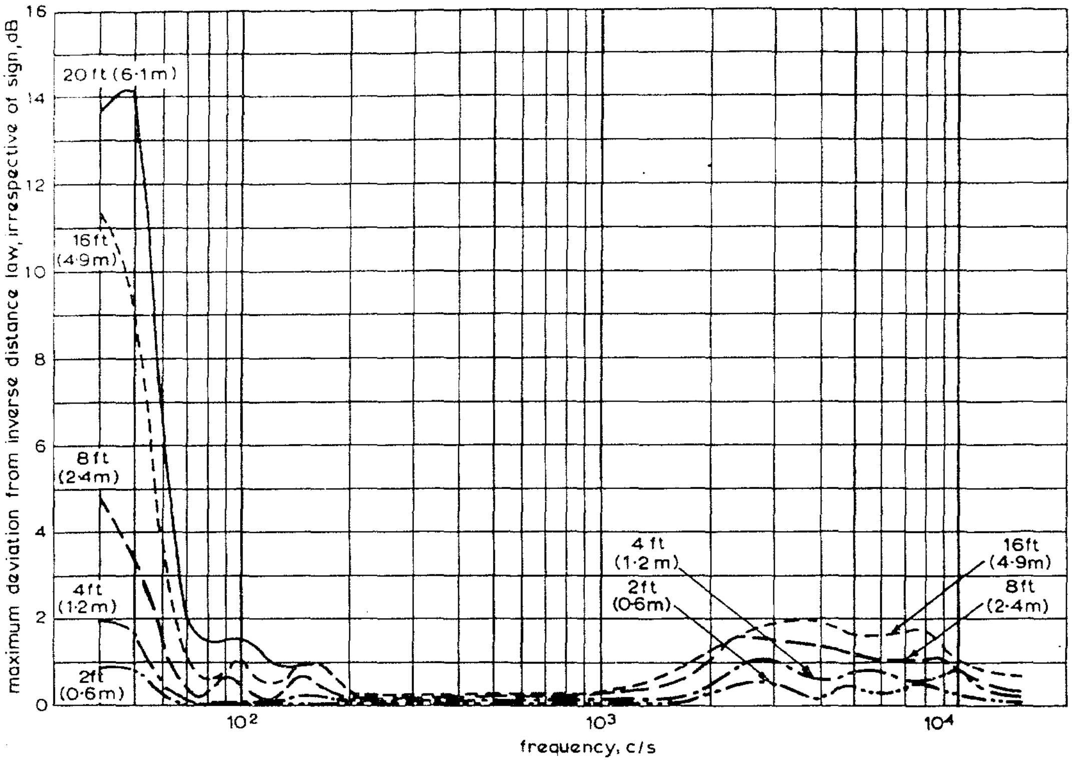


Fig. 11 - Maximum deviation from inverse distance law as a function of frequency, at various distances from sound source: path (a)

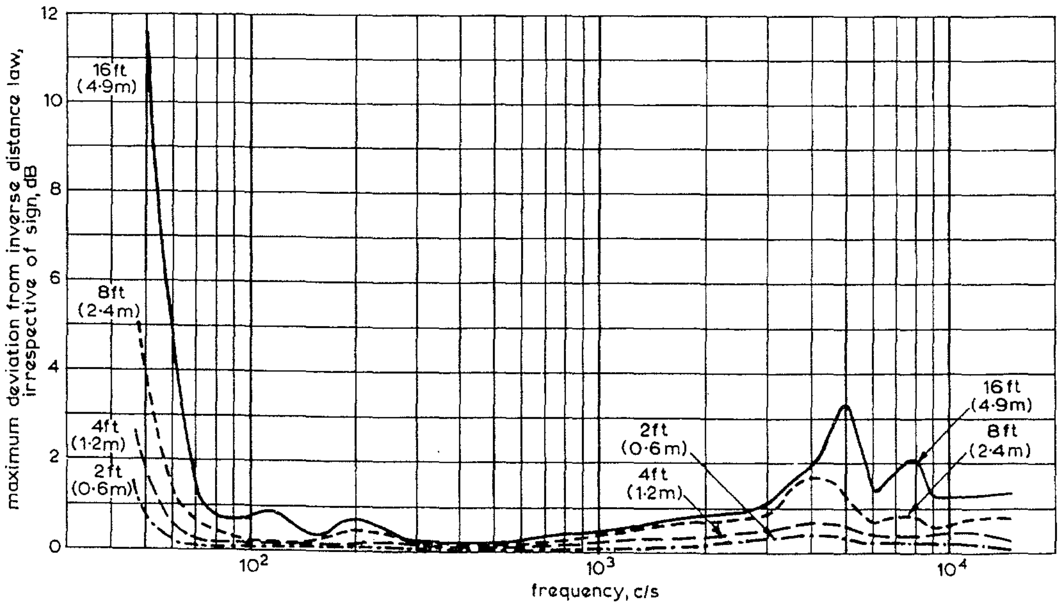


Fig. 12 - Maximum deviation from inverse distance law as a function of frequency, at various distances from sound source: path (b)

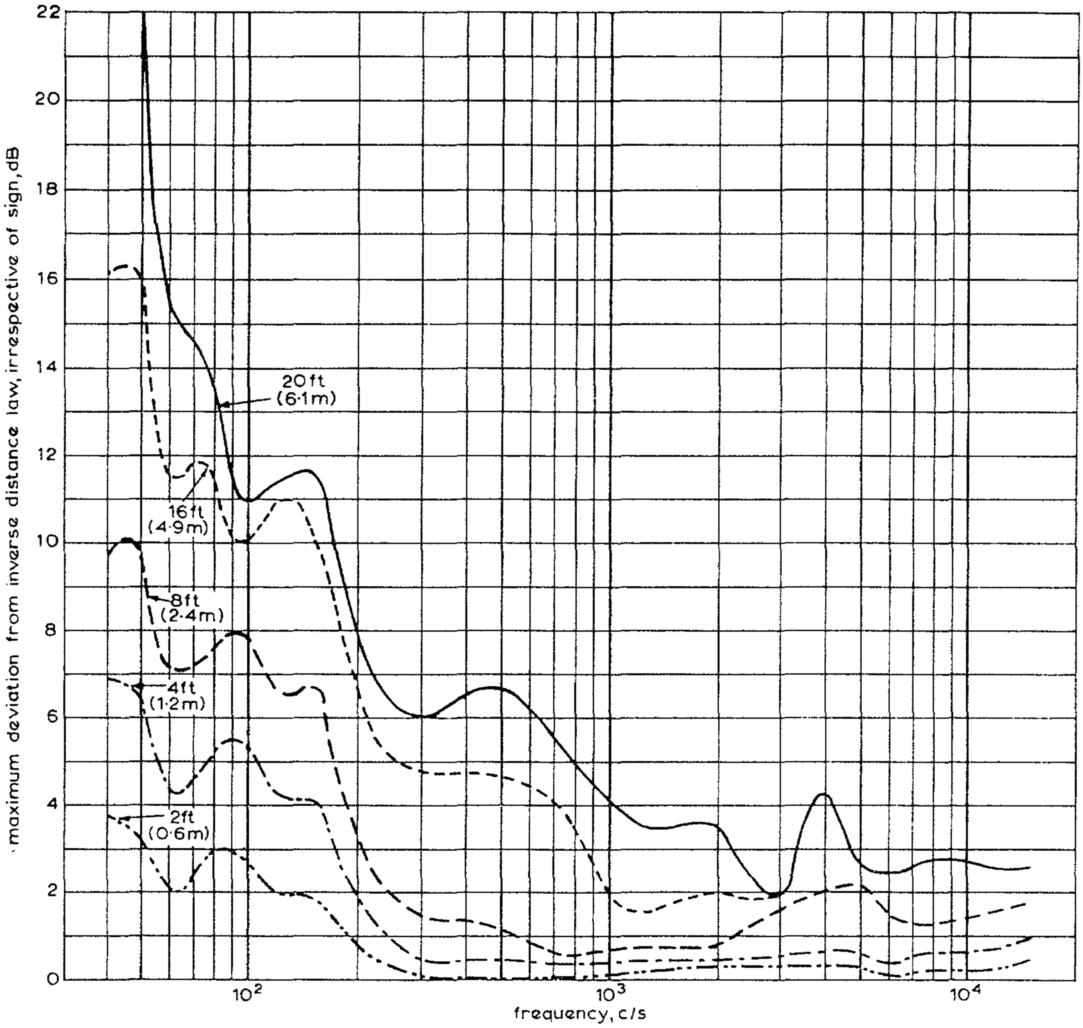


Fig. 13 - Maximum deviation from inverse distance law as a function of frequency, at various distances from sound source: path (c)

is slightly less for path (*b*) along the long axis of the room than along the diagonal path (*a*); a similar difference was found in the Moscow room.[17] In Fig. 13 it will be seen that for path (*c*), close to the wedges, in which most of the sound is at almost grazing incidence to the wedges, deviations from the inverse distance law due to excess attenuation are greater than for the other paths, and at large distances from the source can be observed at frequencies up to 3 kc/s. On the other hand, for distances up to 8 feet (2·4 m), deviations at high frequencies due to standing waves are no greater for path (*c*) than for path (*a*) and at 16 feet (4·8 m) only slightly larger; this result is better than that obtained in the Moscow room. In Fig. 14 it can be seen that for path (*d*) the performance at low frequencies is not quite so good as for path (*a*). In Fig. 15 the effect of the floor gratings on the high frequency performance is indicated for path (*e*); under these conditions it is possible to work only 2 feet (0·6 m) from the source if a standing wave ratio of 1 dB is not to be exceeded at 10 kc/s. Fig. 16 shows the results for the vertical path (*f*). It will be noted that for this path the lateral boundaries are remote from the source;

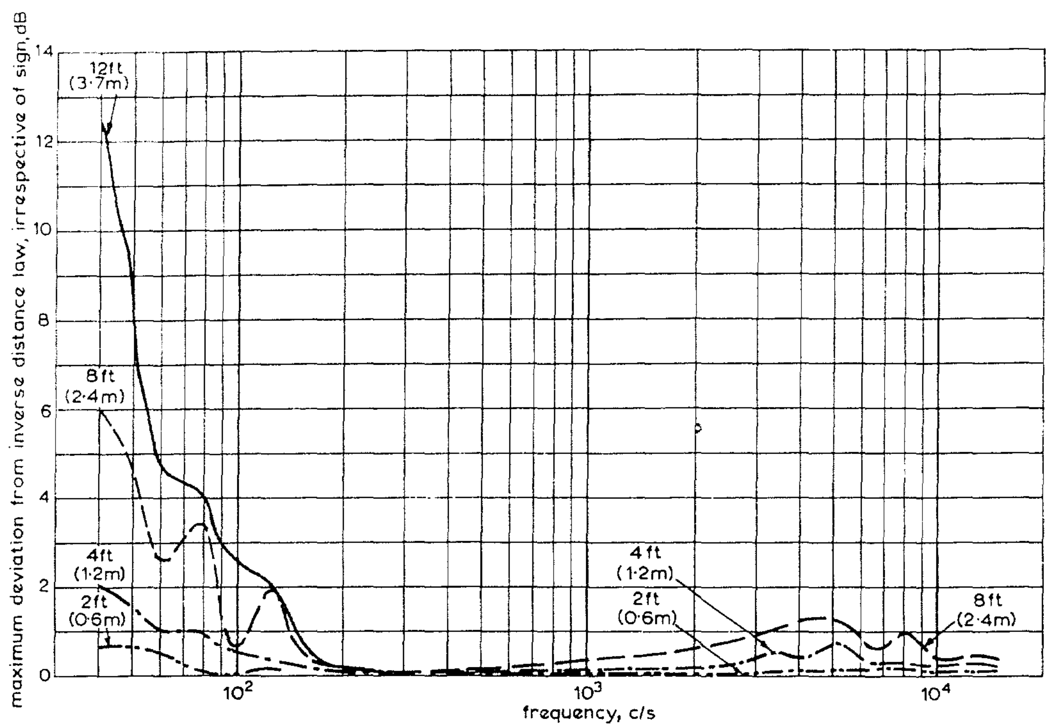


Fig. 14 - Maximum deviation from inverse distance law as a function of frequency, at various distances from sound source: path (d)

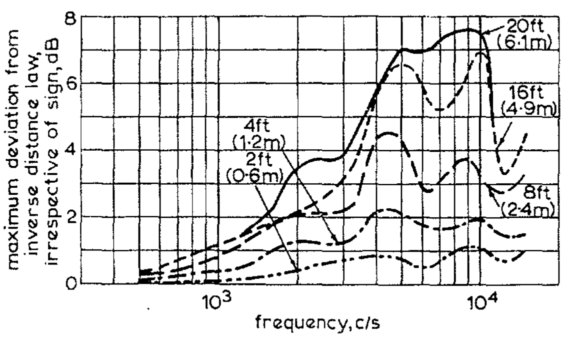


Fig. 15 - Maximum deviation from inverse distance law as a function of frequency, at various distances from sound source: path (e)

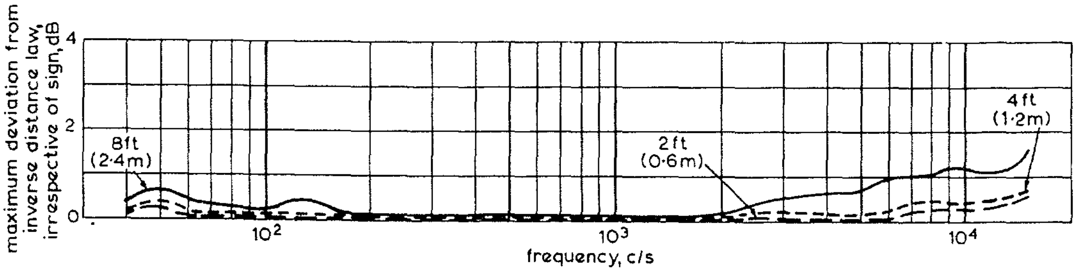


Fig. 16 - Maximum deviation from inverse distance law as a function of frequency, at various distances from sound source: path (f)

as a result the excess attenuation at low frequencies, referred to earlier, is negligible and a close approximation to the inverse distance law is achieved even at 40 c/s.

It will be observed in Figs. 11 and 12 that the deviation from the inverse distance law rises in the 2·5 kc/s to 8 kc/s range. This rise is due to an increase in the amplitude of the standing waves in the room, although no corresponding increase in reflexion factor was found in normal incidence measurements on samples of the wedge material, the results of which, given in Fig. 17, are reproduced from Report No. L-055. It should be noted, however, that at these frequencies sound incident on the sides of the wedges impinges on a flat obstacle of dimensions comparable to or greater than the wavelength; it was calculated from the interference pattern shown in Fig. 10 curve (ii) that the reflexion was taking place from surfaces near the wedge tips on the ceiling and floor and not from the end walls. On the other hand, for path (*f*) the sound is incident much more nearly perpendicular to the treatment and in consequence, as can be seen from Fig. 10 curve (iii), the standing wave effects increase rapidly at the end of the path indicating that the main reflexion comes from the end wall. Other laboratories using wedges of similar width but of different materials have obtained an even greater increase in standing wave ratio in the same frequency range, while in the Moscow room[17], where the wedges are twice the width of those employed in the present case, an increase in reflexion in the 1 kc/s to 3 kc/s range was reported. It seems likely therefore that reflexion from the flat sides of a large number of wedges is cumulative in certain frequency bands and it appears possible that pyramidal absorbers, a form originally used by Meyer[18], might be preferable to wedges in this respect. It should be remembered, however, that in practice both sound sources and microphones are normally directional at high frequencies and this will mean that the effect of the room reflexions will be correspondingly less than that shown.

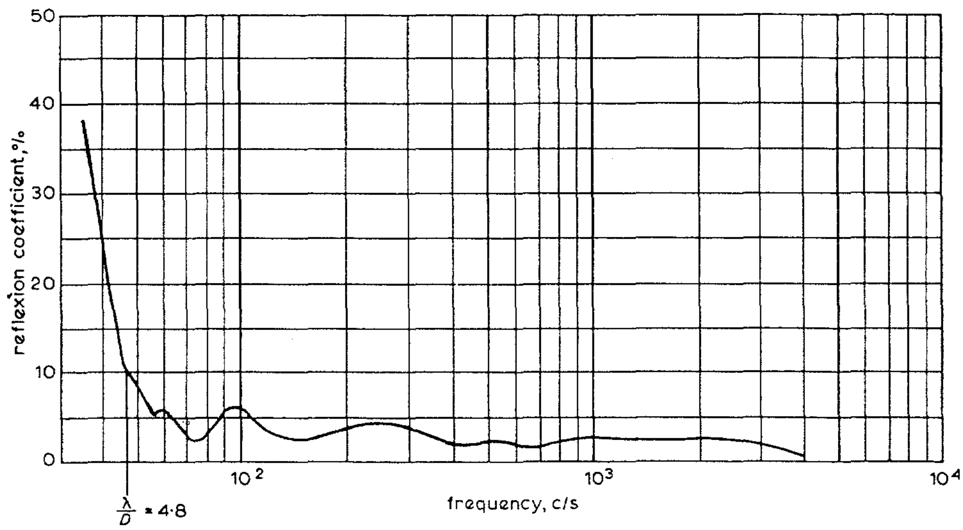


Fig. 17 - Reflexion coefficient of polyurethane wedges, measured at normal incidence, as a function of freqency

6.3. Comparison of Calculated with Experimental Results

It is of interest to compare the above experimental results with those predicted by theory. Olson[19] gives the ratio of reflected to direct energy in a

sound field r cm from a source as

$$\frac{Er}{Ed} = \frac{16\pi r^2}{S \ln(1 - \alpha)}$$

where α is the effective absorption coefficient derived from the reflexion coefficient in Fig. 17, and S is the area of absorbent. The value to be assigned to S is, however, rather uncertain. At the lowest frequencies sound penetrates the absorbent treatment as far as the wall and the surface area of the untreated room appears to be indicated. On the other hand, it is doubtful whether at frequencies above, say, 200 c/s, the incident sound penetrates much further than the base of the tapered position of the wedges. However, as it is in the lower part of the frequency band that the greatest standing wave ratio exists, the surface area of the bare room has been used in calculating the resulting deviation from the inverse distance law; both the calculated and the measured values are shown in Fig. 18. It will be seen that for a distance of 8 feet (2·4 m) from the sound source the calculated values down to 70 c/s are in good agreement with those measured. As already pointed out, the deviation from the inverse distance law shown on the curve below this frequency is mainly due, not to standing waves, but to excess attenuation in the room. If this attenuation is ignored and the standing wave ratio estimated from the measurements, the agreement, shown for example by a single point at 56 c/s, is much closer.

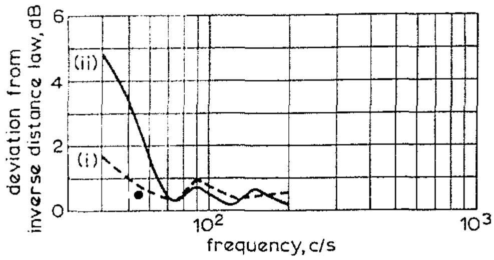


Fig. 18 - Departure from inverse distance law at 8 feet (2·4 m) from sound source

(i) calculated from reverberation formula
(ii) measured over path *(a)*
• estimated from standing wave ratio (single point)

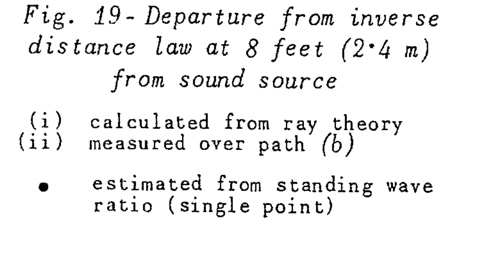


Fig. 19 - Departure from inverse distance law at 8 feet (2·4 m) from sound source

(i) calculated from ray theory
(ii) measured over path *(b)*
• estimated from standing wave ratio (single point)

Deviations from the inverse distance law were also calculated on the basis of ray theory assuming that only one reflexion would be significant. As before, the reflecting surface was assumed, for the purposes of the calculations, to be at the wall; the results are given in Fig. 19 and are seen to be closely similar to those in Fig. 18. It appears therefore that either approach gives a reasonable indication of the departure from the inverse distance law to be expected in the absence of the excess attenuation at low frequencies.

7. CONCLUSIONS

The performance of the new free-field room fulfils the specified requirements. The frequency range over which free-field conditions can be obtained varies with the direction of sound propagation, the lowest cut-off frequency being obtained in the directional parallel to the shortest dimension of the room; it appears that this dimension is a limiting factor in determining the overall performance.

Since the completion of the work described in this report, a new mathematical study[20] of the behaviour of wedge absorbers, taking into account the mechanical properties of the material, has shown that even with cut-off frequencies below 50 c/s, values of λ_0/d approaching 10 can be theoretically envisaged; much more work on materials is, however, required before this possibility can be realized in practice.

For more detailed information on the construction of the free-field room described above, reference may be made to 'The Design and Construction of a Free-Field Sound Measurement Room', Research Department Report now in preparation.

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